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Design of Devices and Manufacturing of Fe-Mn-Si Shape Memory Alloy Couplings

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Abstract

We have studied an Fe-15Mn-5Si-9Cr-5Ni (wt.%) shape memory alloy produced by casting in sand moulds. After processing by rolling at 800° C followed by annealing at 650° C, the structure contains a high density of stacking faults and high strength austenite. When a stress is applied to the material, a reversible martensitic transformation activates before the austenite deforms plastically. Under these conditions, the material recovers about 95% of a 3% permanent deformation. The mechanical properties were measured by tensile tests, giving a yield strength of 350 MPa, an ultimate strength of 880 MPa and 16% total elongation to fracture. Furthermore, the alloy has good weldability using the GTAW method. No macro or micro defects were observed, but there is a 15% deterioration of the shape memory properties due to a heat affected (HAZ) and welded zone (WZ), as measured with bend specimens. In this work, we studied the formability of the material, finding very good performance in simple bending tests. We also present a method for manufacturing couplings by forming and welding, designing forming devices and obtaining the first prototypes. Finally, we evaluated the shape memory properties of the manufactured couplings, finding 83% recovery of a 3.6% diameter expansion. This amount of recovery is suitable for various industrial applications.

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Keywords: shape-memory, Fe-Mn-Si, rolling, martensite, welding

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1. Introduction

The shape memory effect (SME) is observed in some metallic alloys when a stress induced martensitic transformation is reversed by heating. Fe-based alloys are able to exhibit shape recovery through different kinds of martensitic transformations: FCC to BCC or BCT, FCC to FCT, or FCC to HCP; a detailed survey on the subject is provided by Maki's chapter in the book of Otsuka and Wayman (1998). Sato et al. (1982) discovered that high manganese Fe-Mn-Si alloys, which differ in various aspects from commercial steels, have this proper. The stable high-temperature austenitic phase (A, γ, FCC) transforms to ε martensite (HCP) near room temperature. A SME occurs if the stress applied to induce the transformation does not activate plastic slip, and additionally, the $\varepsilon \rightarrow \gamma$ reverse transformation takes place by inversion of the crystallographic path followed during the direct transformation. This behaviour is affected by the austenite yield stress and therefore, by the austenite microstructure. Söderberg et al. (1999), Stanford et al. (2008), and Baruj and Troiani (2008) found an almost perfect SME after rolling at intermediate temperature followed by annealing.

Druker et al. (2010a, 2011a) have investigated a Fe-15Mn-5Si-9Cr-5Ni (wt%) alloy and found that rolling at 800ºC plus annealing at 650ºC produces a structure that contains a high density of stacking faults and an appropriate dislocation density. This promotes the martensitic transformation before plastic deformation of the austenite. After this procedure, the material recovers about 95 % of a 3 % permanent deformation. With respect to technological properties, Druker et al. (2010b, 2011b) reported that the alloy showed good formability and weldability, without macro or microscopic defects. However, SM properties deteriorated about 15% due to the microstructural changes in the fusion (FZ) and heat affected zones (HAZ).

One of the most promising applications of this alloy is for shaft and pipe couplings, particularly where traditional techniques are difficult. Seamless and welded couplings were already developed in China and Japan. These results are documented and summarized by Otsuka and Wayman (1998), Dunne (2012), Awaji (2008), Maruyama (1993, 2008), W. Liu (1999), D.Z. Liu (1997), Hiroshi (2006), and Kajiwara (2003). However, these couplings were not mass-marketed. We are now introducing a new procedure to manufacture welded couplings by forming sheets rolled at 800ºC. We fabricate prototypes and tested them to evaluate the SM behaviour.

2. Experimental procedures

The alloy was melted from commercial-purity material in an induction furnace under a protective argon atmosphere. The chemical composition is shown in Table 1. Carbon content was determined by the combustion technique. Mn and Ni amounts were measured by means of atomic absorption, and the determination of Cr and Si was performed following ASTM standards. After homogenization at 1100ºC for 12 hs, we rolled the ingots at a finishing temperature of 800ºC to a final thickness of 1 mm. The annealing temperature after rolling was 650ºC.

Table 1. Chemical composition of the alloy (wt%).

Fe	C	Mn	Si	Cr	Ni
65.31	0.05	15.43	5.50	8.10	5.61

We measured the material´s hardness using a Shimadzu microdurometer and its mechanical properties by means of tensile tests performed in an Instron 3362 testing machine. Welding was done under an argon protective atmosphere with the TIG method. Our welder is an ESAB, Model Aristo Lud 450, with a 2.4 mm diameter tungsten electrode held in a 10 mm diameter ceramic nozzle. The first coupling prototypes were approximately 40 mm in length and 22 mm in outer diameter (d_0). Fig. 1 shows a finished prototype coupling.

To determine the welded couplings´ SM properties, we expanded them using an elastic sleeve and punch, as shown Fig. 2. The diameter was measured before and after the expansion (d_0 and d_1, respectively), and after annealing (d_2). The degree of shape recovery, DSR_C, was calculated as:

$$DSR_c = \frac{d_2 - d_1}{d_1 - d_0} .100 \quad (1)$$

Fig. 1: Image of the coupling prototype.

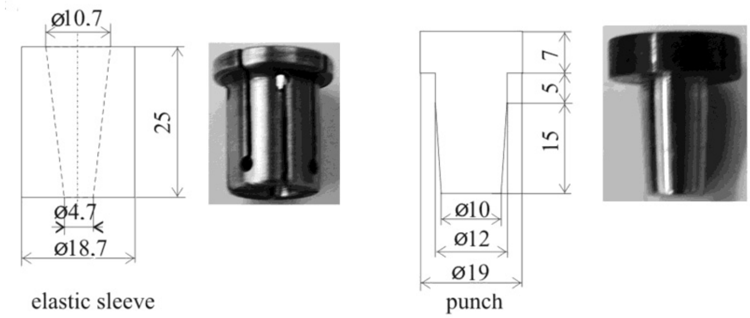

Fig. 2. Shop drawings and images of the tools to expand the couplings.

3. Results and discussion

3.1. Material formability

The first necessary step to manufacture coupling prototypes by plastic deformation of rolled sheets, is to study the formability of the material. As defined by ASM Handbook (1995), formability relates to the ease with which the material can be deformed in normal operations. Formability indices provide quantitative estimates of the mechanical properties of metals (thus, the needed workloads) and the fault resistance. The required properties include those obtained by tensile and other tests designed to simulate various production processes, including cup formation and bending.

Bending is the more common forming mode, and it will be part of our manufacture process. The more important problems of bending are fracture, buckling and wrinkling, also shape distortion, loose metal and undesirable surface textures. The material will become unusable if anyone or combinations of these conditions occur. So, we had to develop formability tests insensitive to the thickness and surface condition of the material.

On one hand, the uniaxial tensile test provides the values of many material properties for a wide range of forming operations, besides tensile properties are useful for mechanical part design and structural calculations. The tensile-test specimens shown in Fig. 3 were cut using the Electrical Discharge Machining (EDM) method from the sheet rolled at 800ºC and annealed at 650ºC, which showed the highest DSR. The curve in Fig. 4 shows that the material deforms elastically to a yield stress of 350 MPa. At this point, permanent deformation begins, due to the $\gamma \rightarrow \varepsilon$ martensitic transformation and/or plastic slip. The Young´s modulus is 123.6 GPa and after yield the hardening rate decreases continuously. A maximum stress of 880 MPa is attained after a total elongation of about 16 % is reached. Finally, brittle fracture occurs.

On the other hand, the bend test is useful when considering the performance of a metal subjected to bending without tension. The simplest method involves clamping a specimen and a bending die in a vise, as shown in Fig. 5, and then bending the specimen over the die, manually or with a nonmetallic mallet. We bent a sample from the 1 mm thick sheet rolled at 800ºC and annealed at 650ºC 180° around a 40 mm diameter die. The corresponding deformation in the outer fibre was 2.5%. No damage appeared after bending, neither evidence of fracture nor surface irregularities.

To investigate whether the martensitic transformation occurs during bending, we heated a bent sample to 550ºC. The reverse transformation activated, and the material recovered 157º of the original 180º, which represents a DSR of 87%. This is a good result with respect to the performance finished couplings, but it may indicate that distortion can occur during manufacturing.

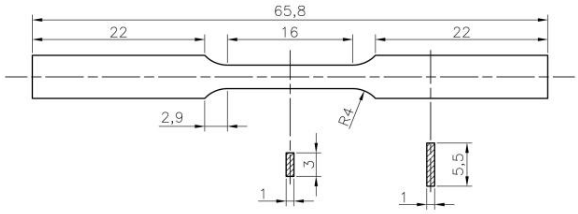

Fig. 3. Tensile test specimen

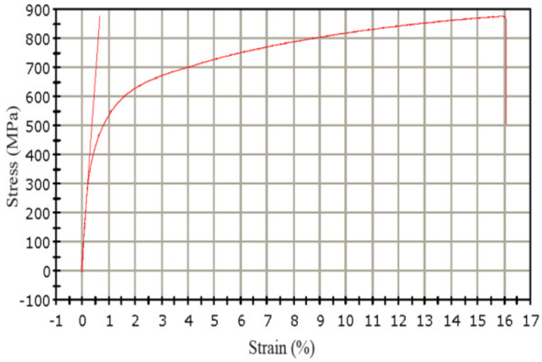

Fig. 4. Stress-strain curve obtained by tensile testing a sample rolled at 800º C and annealed at 650º C.

3.2. Manufacturing of coupling prototypes

3.2.1. Die design

Fig. 6 shows the assembly plane of the manufacturing device for producing the first prototypes of shape memory couplings. It was designed to work on the laboratory scale and is used with a manually operated hydraulic press.

The device has four parts: upper and lower dies, a punch, and a bridge. To fabricate the dies and punch we selected a plain, medium-carbon steel (SAE 1045). After machining, we quenched the parts in water and tempered them to HRc 48. The bridge was built of SAE 1010.

We formed the sheet in successive stages in the lower die, curving it around the punch, which was horizontally supported by the bridge. Finally the upper die replaced the bridge, completing the tubular shape. Fig. 7 shows three successive steps of the forming procedure.

When we opened the dies, the material sprung back elastically, as shown in Fig. 8a. After heating to 550ºC, the reverse transformation activated and the sheet partially recovered its flat shape (Fig. 8b). It is important to consider how the SME can affect the manufacturing process, especially due to heating during welding. High stresses can be generated in the seams and cracks of the welded tube.

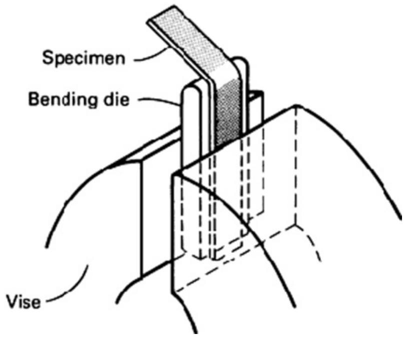

Fig. 5. Schematic of the simple bend test, taken from ASM Handbook (1995)

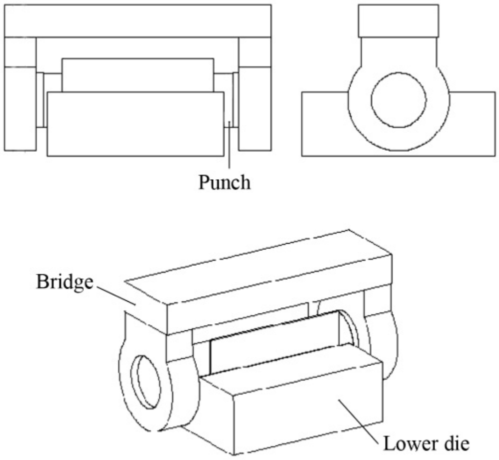

Fig. 6. Assembly plane of the compound bending die.

Fig. 7. Three steps during the forming procedure.

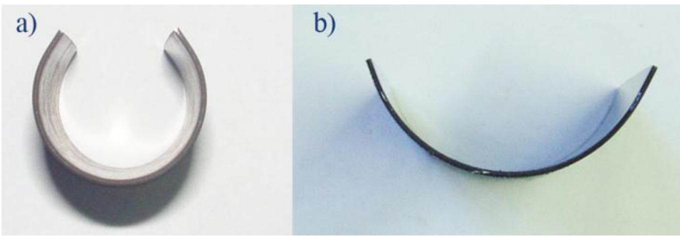

Fig. 8. a) Elastic recovery and b) SM recovery, shown during manufacturing.

Fig. 9. Redesigned bending die to maintain the pressure during heating.

To assure that the main deformation introduced into the sheets is plastic, we added threaded holes to accommodate stud bolts adjusted with wing nuts (Fig. 9). Once the lower and upper dies were completely shut, we adjusted the wing nuts to fix them in place. Then, we heated the closed assembly to 550ºC, above the reverse transformation temperature. The closed die/punch system prevented shape recovery and the stress developed within the fixture plastically deformed the austenite. This occurs because the alloy is above the M_d temperature.

3.2.3. Welding

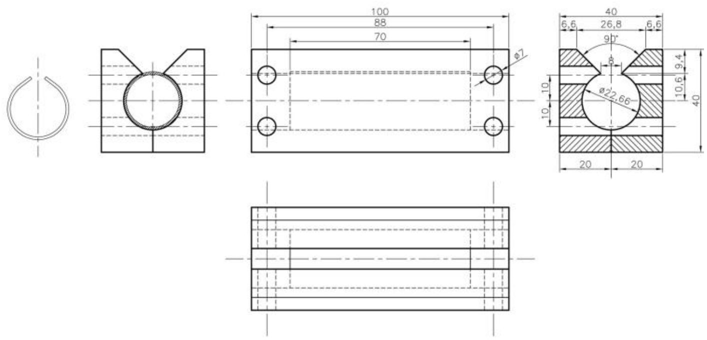

Fig. 10. Design of a device to hold the tube for welding.

To finish the manufacture of couplings, sheets formed into tubes need to be welded. Fig. 10 shows a device especially designed to hold the tube in position during welding and to compensate for springback, which occurs when the part is removed from the forming die. Fig. 11 shows the sequence of operations and conditions in the welding process.

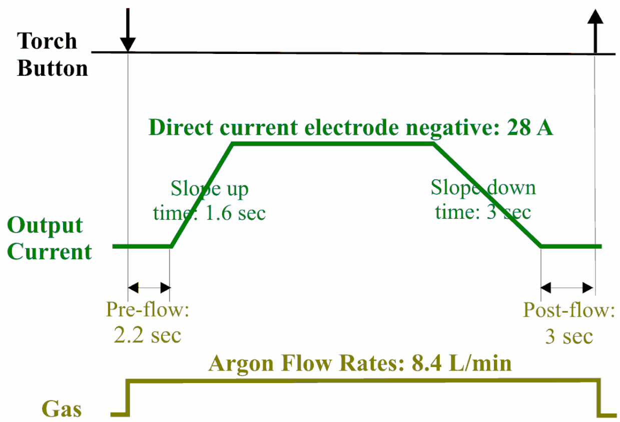

Fig. 11. Processing sequence and welding conditions

3.3. Degree of shape recovery

Circumferential expansion is the first stage for determining the coupling's SM behaviour. As explained previously, we did this by applying loads with the Instron 3362 testing machine to the tapered punch head inserted in the elastic expansion sleeve. Movement of the punch opens the sleeve deforming the coupling. We prepared different batches of samples by annealing at 650, 800 and 1000ºC for 30 min after welding, tested them, and calculated the ***ER*** (amount of elastic recovery, %), $\boldsymbol{\varepsilon}$ (permanent deformation, %) and ***DSR*** (degree of shape recovery, %). Table 2 shows the results, which are plotted in Fig. 12.

Table 2. Degree of shape recovery of couplings annealed at different temperatures

	d_0 (mm)	d_e (mm)	d_1 (mm)	ER (%)	d_2 (mm)	ε (%)	DSR (%)
Annealed at 650ºC	22.03	22.90	22.70	0.9	22.17	3.0	79
Annealed at 800ºC	21.82	22.78	22.61	0.77	21.95	3.6	83
Annealed at 1000ºC	22.38	23.18	23.13	0.22	22.77	3.35	48

In Table 2, $\mathbf{d_0}$, $\mathbf{d_e}$, $\mathbf{d_1}$ and $\mathbf{d_2}$ are respectively, the outer diameter before expansion, during expansion, after elastic recovery, and after heating for shape recovery.

The couplings´ DSR depends on the annealing temperature. Annealing at 1000ºC gives a DSR of only 48%, a poor value due to the softening of the austenitic matrix. Annealing at 800º C gave the best SM behaviour. A recovery of 83% of a permanent deformation of 3.6 % was obtained, which is enough for many industrial applications. The couplings annealing at 650º C performed nearly as well, achieving a shape recovery only 13 % less than for those annealed at 800ºC. The 13 % decrease could be due to welding residual stresses.

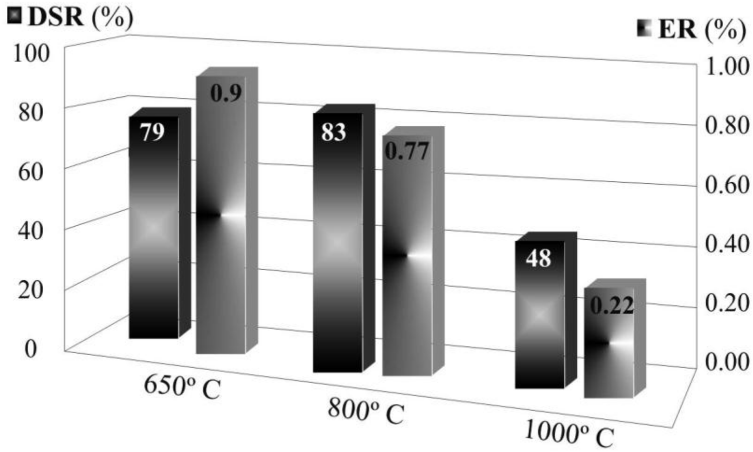

Fig. 12. Results of the shape memory tests for the couplings. DSR: degree of shape recovery. ER: elastic recovery.

4. Conclusions

We have investigated the mechanical, technological and recovery properties of ferrous shape memory alloy couplings. We found that:

1) The Fe-15Mn-5Si-9Cr-5Ni alloy rolled at 800ºC and annealed at 650ºC has appropriated formability and weldability.

2) A new method to manufacture welded couplings was introduced and tested, with satisfactory results.

3) The DSR of the couplings manufactured by this method depends on the annealing temperature after welding. Couplings annealed at 800ºC recovered 83 % of a diametric expansion of 3.6 %.

In light of these promising results, we are continuing to develop this SME technology.

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